

Thermal Behavior of Aerospace Spur Gears in Normal and Loss-of-Lubrication Conditions

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ABSTRACT

Testing of instrumented spur gears operating at aerospace rotorcraft conditions was conducted. The instrumented gears were operated in a normal and in a loss-of-lubrication environment. Thermocouples were utilized to measure the temperature at various locations on the test gears and a test utilized a full-field, high-speed infrared thermal imaging system. Data from thermocouples was recorded during all testing at 1 Hz. One test had the gears shrouded and a second test was run without the shrouds to permit the infrared thermal imaging system to take data during loss-of-lubrication operation. Both tests using instrumented spur gears were run in normal and loss-of-lubrication conditions. Also the result from four other loss-of-lubrication tests will be presented. In these tests two different torque levels were used while operating at the same rotational speed (10000 rpm).

INTRODUCTION

Drive systems in all rotorcraft are subjected to many qualification tests that must be passed to the satisfaction of the current Aeronautical Design Standard (Ref. 1). One of the most difficult tests is the loss-of-lubrication test after the primary lubrication system has been disabled. In some cases the drive system will need to either be modified or an auxiliary lubrication system be configured to help the drive system pass the 30 min requirement. In many cases this will result in an increase in system cost initially and may require additional drive system complexity. Basic research on this type of testing has been limited in the open literature due to the proprietary nature of the modifications that are applied to successfully pass the testing requirements.

Work has been on-going for some time at the NASA Glenn Research Center with the main results being generated on spur gears (Refs. 2 to 4). These tests involved using aerospace quality gears that then had the inlet lubricating jet shut off and the time to failure was measured (loss of torque typically was when the test was stopped). In the tests of Reference 4, tests were concentrated on incrementally making the test simulation operate in what would be considered an aerospace environment. In some follow-on testing an instrumented spur gear was tested in normal and loss-of-lubrication conditions (Ref. 5).

The objective of this paper is to describe testing with an instrumented spur gear operating at 10000 rpm, and 59.3 N*m (525 in*lb) torque and in normal and loss-of-lubrication conditions. A total of six tests will be presented in this report. Two tests were conducted using thermocoupled spur gears. One of these tests had the gears shrouded and the other was run unshrouded. Also four more tests were

conducted using the same shrouding and operating speed but were conducted at two different torque levels.

TEST FACILITY

The test facility used for conducting all loss-of-lubrication simulation tests is the NASA Glenn Contact Fatigue Test Facility (Refs. 6 to 8). The facility is shown in the sketch illustrated in Figure 1. The facility is a closed-loop, torque regenerative test rig that locks torque in the loop via a rotating torque applier contained within one of the slave gears. The test gears have a 1:1 ratio. Facility speed and torque can be varied as needed during a test. The basic gear design information of the tested gears is listed in Table 1.

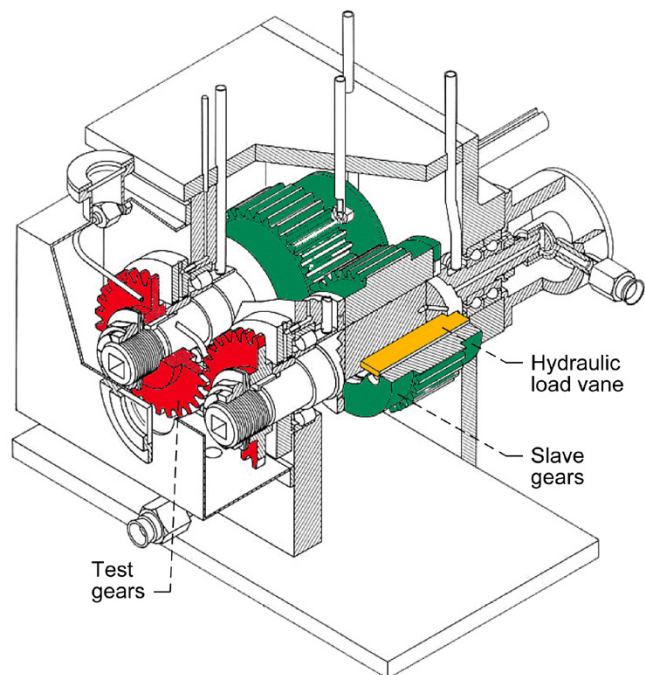


Figure 1. Cross-sectional sketch of the test gearbox used for loss-of-lubrication testing.

As previously mentioned, the facility went through an evolutionary period (Ref. 4) where shrouding, visual access, gearbox lubricant removal (sump), and instrumentation were added to the test section. A photograph of the current test gearbox arrangement is shown in Figure 2.

Table 1. Basic Gear Design Information.

28 tooth gear	
Module, mm (diametral pitch (1/in.))	3.175 (8)
Pressure angle (deg.)	20
Pitch diameter, mm (in.)	88.9 (3.5)
Addendum, mm (in.)	3.175 (0.125)
Whole depth, mm (in.)	7.14 (0.281)
Chordal tooth thickness, mm (in.)	4.85(0.191)
Face width, mm (in.)	6.35 (0.25)



Figure 2. Top exit shrouds with normal lubrication conditions.

Three static shroud thermocouples were utilized during all tests. High temperature glass was also utilized as the outside shroud to encase the gears. Ballistic plastic and another layer of high temperature glass provided visual (and video) access to the gears during operation. Lubricant for normal operation was fed at the into-mesh location through part of the shroud (Figure 3). The normal operational flow rate was approximately 0.42 l/min (0.11 gpm) at 207 kPa (30 psig) jet pressure with the lubricant inlet temperature of $\sim 110^{\circ}\text{C}$ (230°F). The static instrumentation used and normal lubricant jet locations are shown in Figure 3. A turbine engine-drive system lubricant, MIL-L-85734, was used during the testing to be described in this report.

TESTING METHODOLOGY

From prior loss-of-lubrication tests as described in References 4 and 5, and discussed in this paper, the gears were broken-in to allow normal run-in wear to occur. The gears were operated for at least 1 hr at $\sim 50\%$ of maximum torque and at full facility speed (10,000 rpm). After this period, the torque was then increased to the maximum and run for at least several more hours prior to conducting a loss-of-lubrication test. Most tests were run until the teeth failed to continue to carry torque (plastically deformed) or stopped just prior to this condition.

For the instrumented gears used in this report, the break-in and then run at higher torque procedure was not followed due to the instrumentation and slip ring limited life. During all tests, the static instrumentation and live video were carefully monitored. Data from all sensors were recorded at 1 Hz and stored for post-processing.

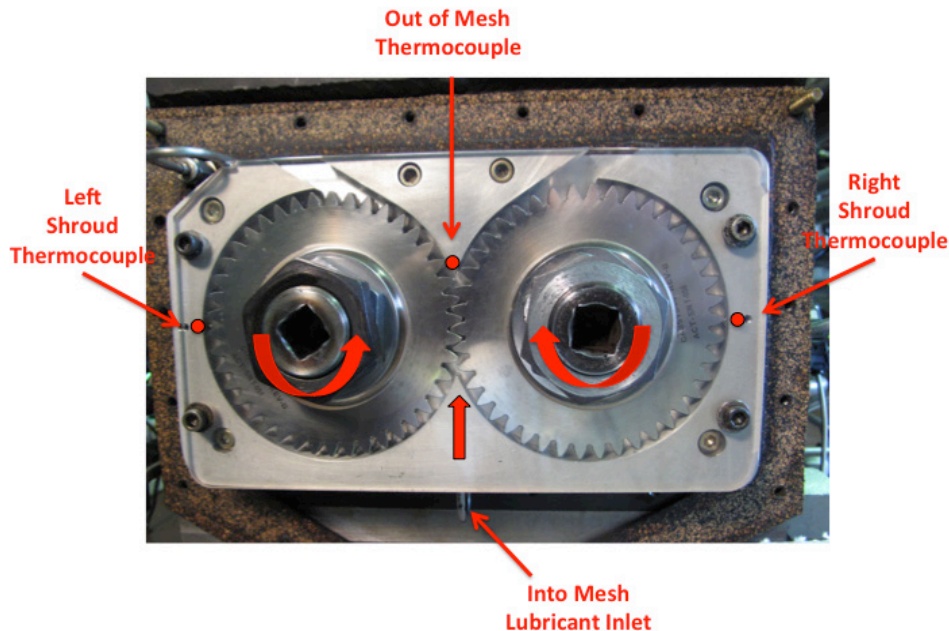
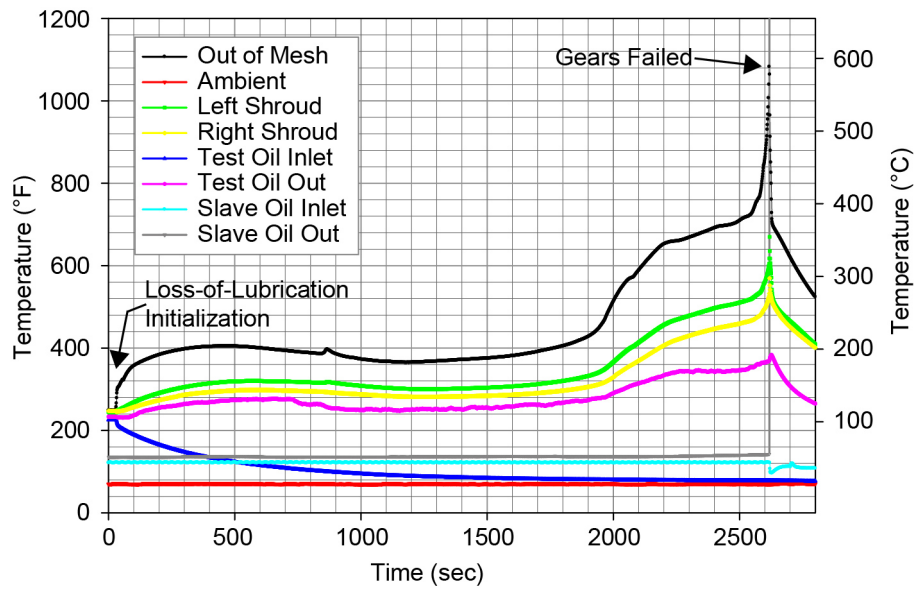


Figure 3. Example of test gear arrangement with outer gearbox cover removed, top exit shrouds shown (12 pitch gears shown).



**Figure 4. Loss-of-lubrication data for 1.72 kPa (250 psi) load pressure
~ 59.3 N*m (540 in*lb) torque tested at 10000 rpm.**

Test Gears

The test results to be described in this report were from the same lot of gears manufactured to the basic gear design information as shown in Table 1. The gear material was an aerospace gear steel (Ref. 9) that was carburized and final ground. The surface roughness was $0.41 \mu\text{m}$ (16 $\mu\text{in.}$) or better. The gears have some tip relief starting at the highest point of single tooth contact ($\sim 38 \mu\text{m}$ (0.0015 in.) maximum) and a small amount of crowning (5 μm (0.0002 in.)) symmetric across the face width.

Baseline Loss-of-Lubrication Tests

A total of four test results will be described in this section of the report. Two more tests using the instrumented gears will be described later. The tests in the loss-of-lubrication condition were conducted at one of two torque levels as documented in Table 2. The gear basic design information along with the load level produced maximum level of bending and contact stress found via the analysis technique of Reference 10.

Table 2. Test Condition Stress Analysis Results (Ref. 10).

Torque N*m (in*lb)	Maximum contact stress, GPa (ksi)	Maximum bending stress, GPa (ksi)
59.3 (525)	1.67 (242)	0.214 (30.9)
83.6 (740)	1.88 (272)	0.296 (43)

An example of each of the two torque levels will now be described. At the lower torque level, two tests were conducted with the loss-of-lubrication times of 40.8 and 43.1 min in length. Note that in Figure 4, the gears reached another level of operating temperature that appeared to be a new “steady state” condition where the out-of-mesh temperature stabilized at around $\sim 200^\circ\text{C}$ (400°F). This elevated steady state condition is believed to be due to residual lubri-

cant left in the shroud. This occurs even though the shrouds effectively pump the excess lubricant out to the rest of the gearbox housing. The data from the static thermocouples imbedded in the shrouds along with other facility temperatures is shown in Figure 4.

The gears in the post-test condition are shown in Figure 5. Note that the test was conducted until the meshing heat generation was enough to plastically deform the gear teeth. This type of post-test condition occurred whenever the test was permitted to continue until total loss of torque delivery was achieved. A typical loss-of-lubrication failure at this condition is shown in Figure 6.

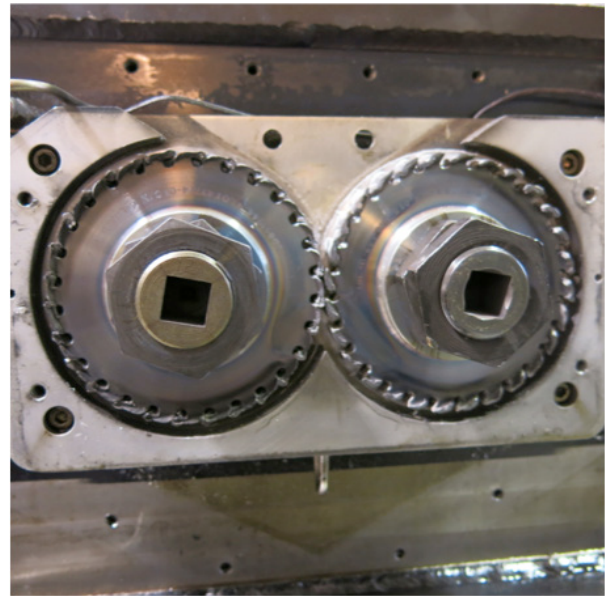


Figure 5. Post-test condition of the gears (gearbox cover and outer high temperature glass removed).

Two other tests were conducted at an elevated level of torque ($\sim 83.6 \text{ N}\cdot\text{m}$ ($740 \text{ in}\cdot\text{lb}$)). These two tests, in the loss-of-lubrication mode, produced failures in 7.9 and 9.2 min. The test temperature data from the 7.9 min loss-of-lubrication test is shown in Figure 7. As can be seen from this data, the temperature did not reach an increased steady-

state condition prior to failure as it did in the test shown in Figure 4. After the primary lubrication system was disconnected the temperature just continued to rise. The post-test condition of the test gears is shown in Figure 8 with the gearbox cover removed.

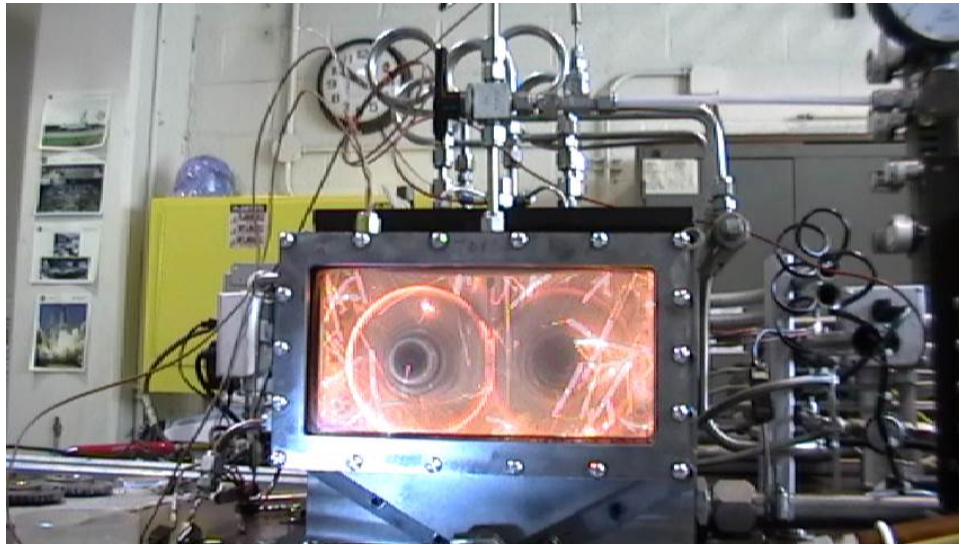


Figure 6. Example of loss-of-lubrication test during final seconds of operation.

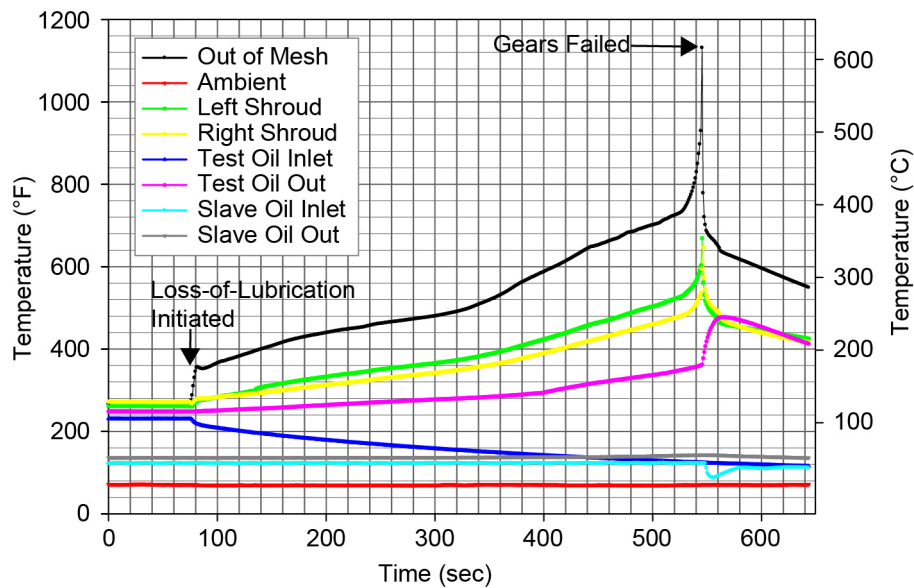


Figure 7. Loss-of-lubrication data from higher load test $83.6 \text{ N}\cdot\text{m}$ ($740 \text{ in}\cdot\text{lb}$).

Instrumented Test Gears

A loss-of-lubrication test with on-component information is the most desirable. However, instrumentation on the gear-meshing surface has been shown to be very difficult to accomplish. Even with full elastohydrodynamic (EHD) film the lubricant viscosity of aerospace turbine engine lubricants, as used in rotorcraft drive systems, is insufficient to develop EHD films thick enough to keep the on-surface instrumentation from wearing away (Ref. 11). Therefore, thermocouples were installed at locations in areas of the gear where contact does not occur, and therefore could be used for future modeling efforts.

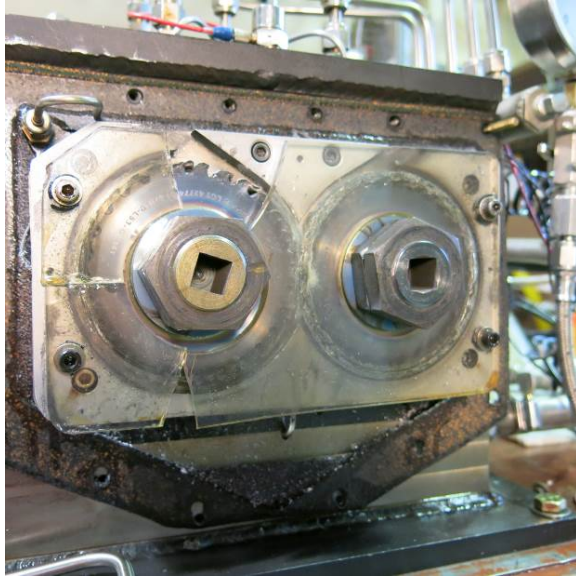


Figure 8. Post-test photograph of increased load test gears with outer shroud high temperature glass fractured.

An example of the gears used in these tests is shown in Figure 9. In both tests, the instrumented gear was installed in the left side of the gearbox. The left side gear acts as the driving gear of the test section of the facility. A total of five thermocouples were attached to the gear at the tooth tip mid-face width, root mid-face width, and on the side of the gear at the pitch radius, root radius and mid-web locations. As shown in Figure 9, the thermocouple wires were covered by a thin metal foil that was spot welded to the side of the gear to protect the instrumentation during high-speed operation. The rest of the required hardware is shown in Figure 10 prior to installation in the test rig. This included a special gear shaft, high-speed coupling, and high-speed slip ring. The assembly in the test rig is shown in Figure 11. Note that keeping the slip ring contacts in the same ambient condition is important to getting reliable data. Therefore the slip ring was insulated from the surroundings using a polycarbonate tube and an insulating material added to block the tube end.

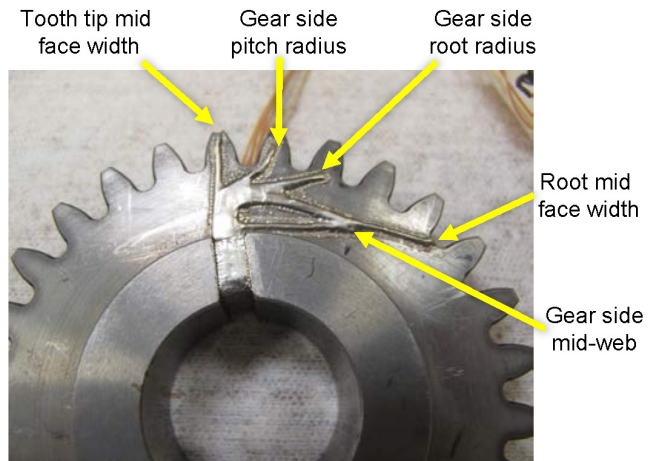


Figure 9. Instrumented loss-of-lubrication Test Specimen before testing.

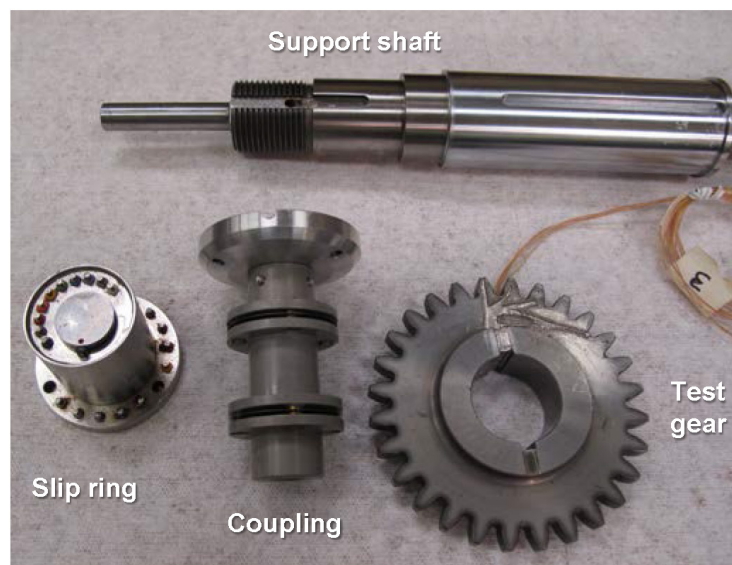


Figure 10. Loss-of-lubrication test specimen and related components.

Also, on the second instrumented spur gear test, a full-field, high-speed, infrared thermal imaging system was used. This system had the potential to capture full-field thermal images at speeds over 500 Hz. A special lens was inserted into the gearbox cover to gain visual access to the gears operating in the unshrouded condition (Figure 12).

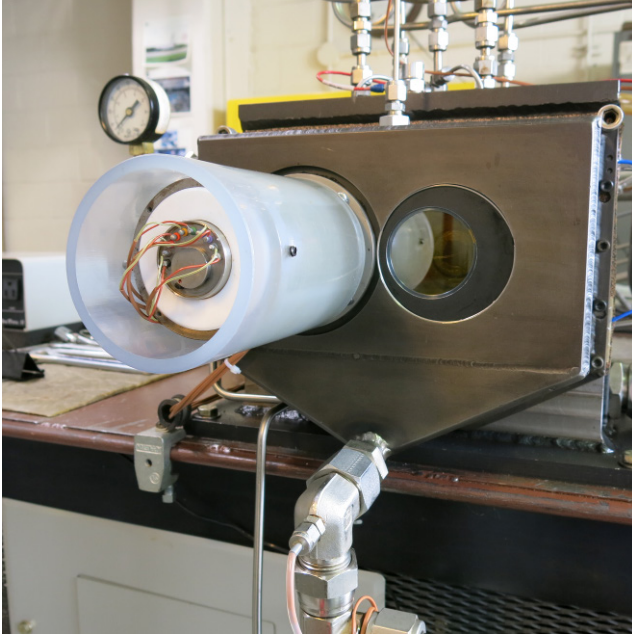


Figure 11. Test Set up for Instrumented Test Gear

Instrumented and Shrouded Gear Results

The data for operation of the facility in the shrouded, normal to loss-of-lubrication mode is shown in Figure 13. During this test the lubricant was shut off and the test run until failure. The data from loss-of-lubrication initiation to failure for the shroud (static) and other facility thermocouples is shown in Figure 14.

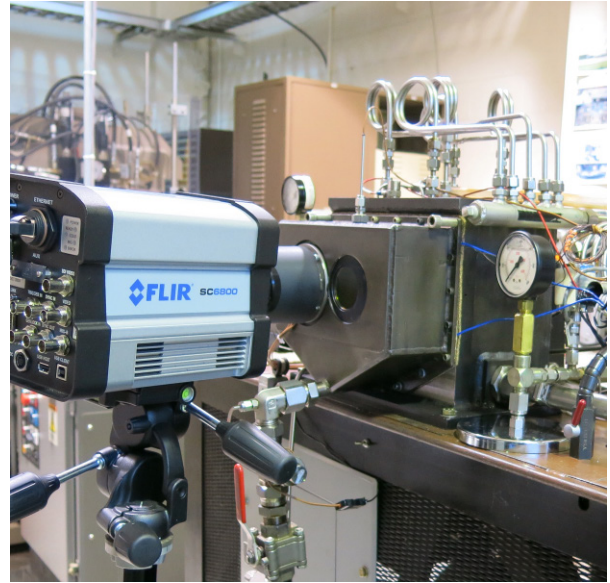


Figure 12. Infrared Camera in position for loss-of-lubrication test.

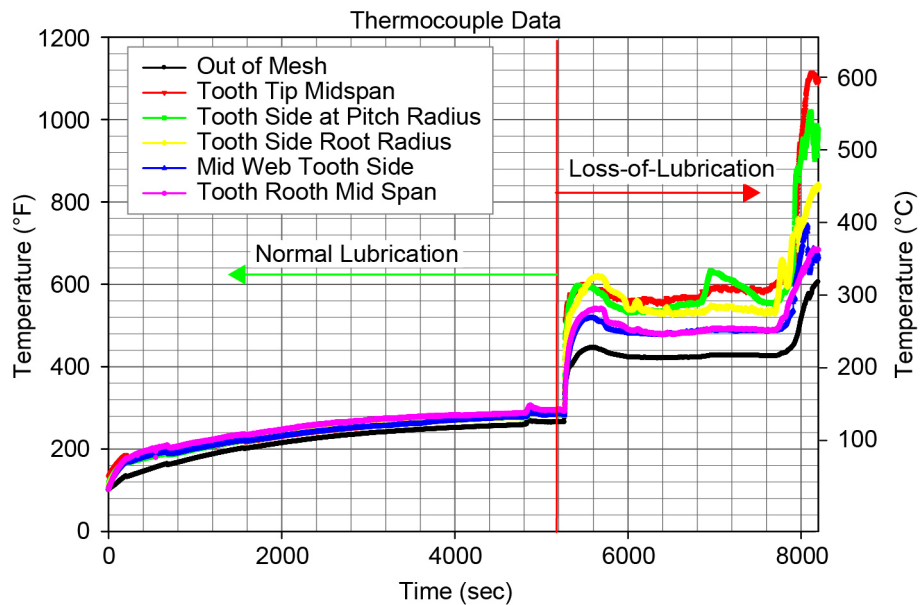


Figure 13. On-gear and out-of-mesh thermocouple data from start-up to instrumentation failure during loss-of-lubrication.

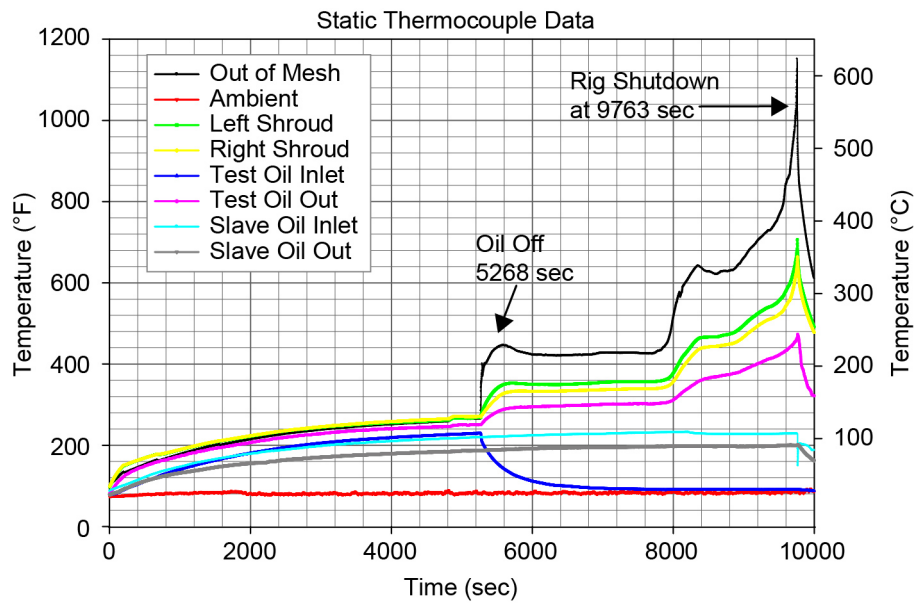


Figure 14. Data from shroud and facility (static) thermocouples.

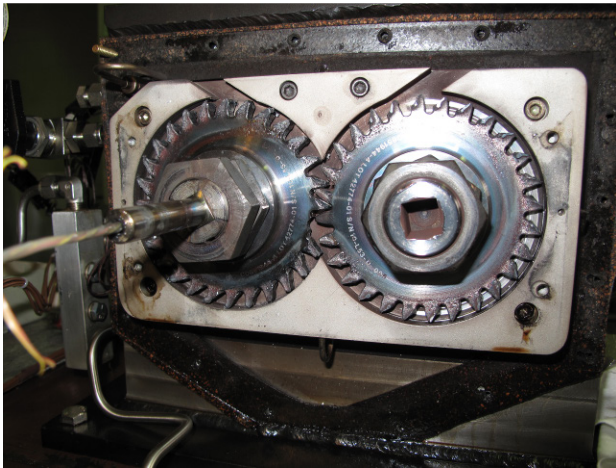


Figure 15. Post-test condition after loss-of-lubrication test was completed. Gearbox housing, slip ring and outer high temperature glass removed.

From the data in Figure 13 and Figure 14, the bulk temperatures of the gear were exceeding the temperature that was found from the static shroud thermocouples. In the normal lubrication condition this value was 11 to 22 °C (20 to 40 °F) depending on the location. In the loss-of-lubrication mode, this amount was as high as 275 °C (500 °F) higher on the gear than that of the static shroud thermocouples when the thermal run-away condition occurred. In Figure 13, the data beyond 8200 sec is believed to be invalid due to post-test inspection of the thermocouple wiring that was melted together at the common locations through the shaft.

The post-test condition of the gears used in this test is shown in Figure 15. What can be noted is that a bending failure occurred before the loss-of-lubrication test, as the failed tooth has no evidence of running in this post-test

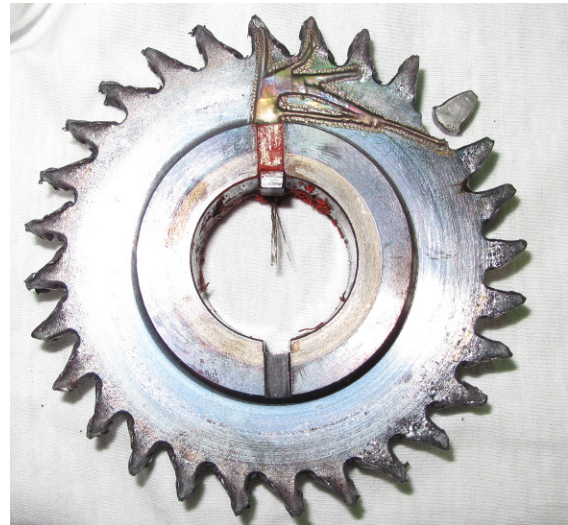


Figure 16. Instrumented spur gear post-loss-of-lubrication test condition.

condition. A hypothesis is that the failed tooth was initiated by a spot weld in the root-fillet region from the thin metal protection strap that was used to cover the thermocouple wiring as shown in Figure 16.

In Figure 16, the tooth that failed in bending shows no apparent damage due to loss-of-lubrication since it occurred before this lubrication condition was initiated. Upon closer examination, the thin metal strapping used to overcoat the wiring and spot-welded to the tooth, was found to be the initiation site of the bending failure. Future test hardware for this purpose will not have this as a hold-down feature for the tooth root-fillet area.

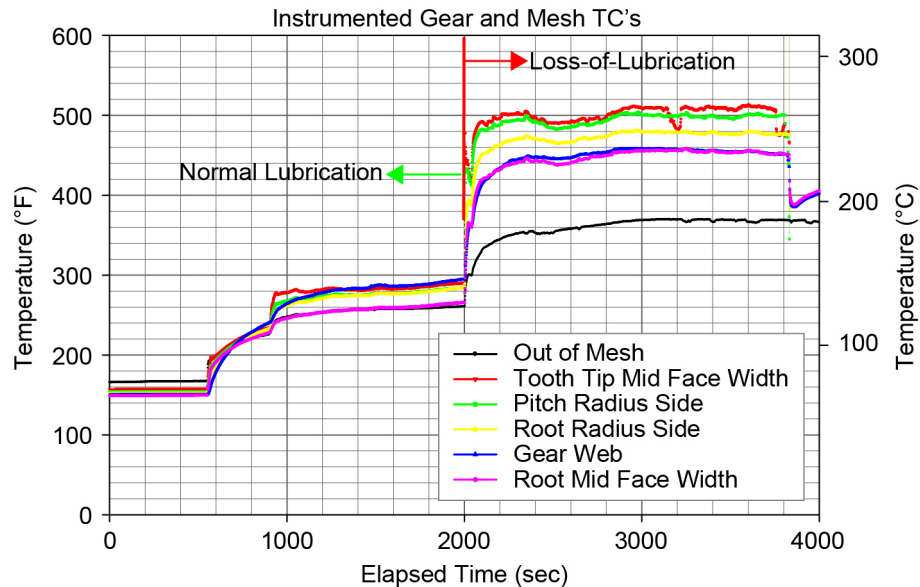
Instrumented, Unshrouded Gear, and Infrared Thermal Image Results

A second instrumented test gear with thermocouples imbedded at the same locations as the first test mentioned in this report was installed and prepared as mentioned in the earlier test. In this test, however, the use of a full-field infrared thermal imaging system was used. Data from the thermocouples and infrared system will now be described.

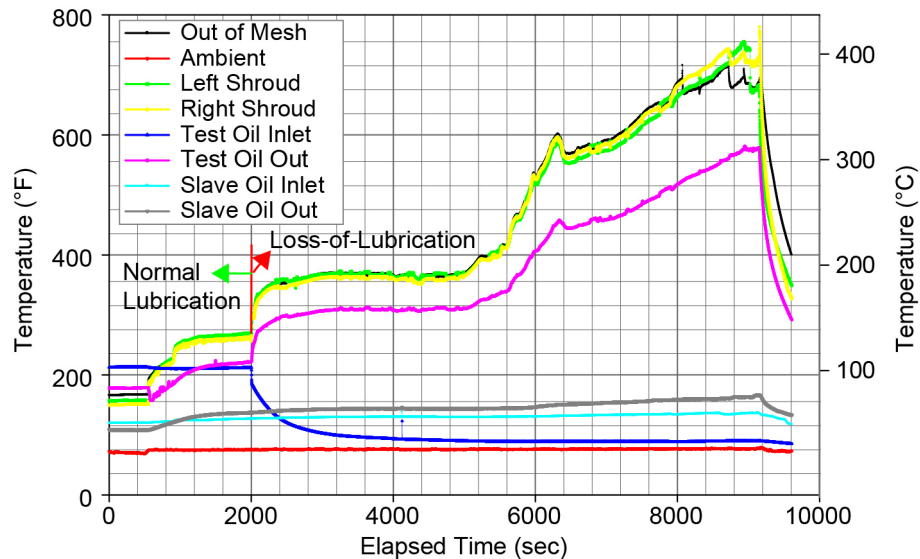
Thermocouple Data: The thermocouple data attained appeared to be similar to the shrouded gear data with the

unshrouded data being slightly lower during the normal and loss-of-lubrication periods. For this test the thermocouple data failed at 3800 sec into the recorded data. This data is shown in Figure 17.

The results from the static thermocouples at the same locations as the shrouded gear tests are shown in Figure 18. As can be seen in Figure 18, the gears reached an elevated steady state, mesh fling-off temperature of approximately 180 °C (360 °F) before the temperature started increasing in a monotonic rate until the test was stopped.



**Figure 17. Instrumented spur gear data (no shrouds).
Loss-of-lubrication initiated at 2000 sec.**



**Figure 18. Static thermocouple data from instrumented spur gear test
(no shrouds). Loss-of-lubrication initiated at 2000 sec.**

Comparing the on-component results from the two different instrumented gear tests showed that the unshrouded gear operated at similar temperature during normal lubrication conditions. At and during loss-of-lubrication conditions, the unshrouded gear operated $\sim 45^\circ\text{C}$ (80°F) cooler than the shrouded gear during the “steady state” elevated temperature operation period.



Figure 19. Post-test condition of unshrouded and instrumented spur gears.



Figure 20. Close up of instrumented and unshrouded gears post-test.



Figure 21. Close up of gearbox cover post-test for unshrouded gear test.

The post-test condition of the test gears is shown in Figure 19. Note that several gear teeth had failed (one on the driver (instrumented) and five on the driven gear). A close up of the gear condition is shown in Figure 20. Also, the post-test condition of the gearbox cover is shown in Figure 21. Note that there is virtually no lubricant to be found.

Infrared Thermal Image Results. As mentioned earlier, a full field, high-speed, infrared thermal imaging system was utilized in the second instrumented spur gear test. A test without shrouding was necessary as the high-temperature glass filtered or obscuring the gears due to the transmissibility of the clear (visually) shroud cover. A special lens with almost 100% transmissibility at the infrared wave lengths of interest was installed in the gearbox cover.

Data was taken only after operation in the loss-of-lubrication mode. This is when the lubricant being flung off the meshing gears did not obscure the lens located in the test gearbox cover. Also, the camera was synchronized to the rotational speed of the test gears (167 Hz) to essentially “strobe” the gear and then the images were recorded the full-field data at a rate of 1 Hz. Two examples of the data are shown in Figure 22 and Figure 23. Figure 22 was taken early in the loss-of-lubrication period. Figure 23 was taken later in the loss-of-lubrication period as the temperature recorded as the gear teeth temperatures were in excess of 370°C (700°F). The data taken appears to be in agreement with that taken via thermocouples as shown in Figure 17. Therefore, the use of this type of instrumentation will be invaluable for thermal models now under development, as full field information can be made available.

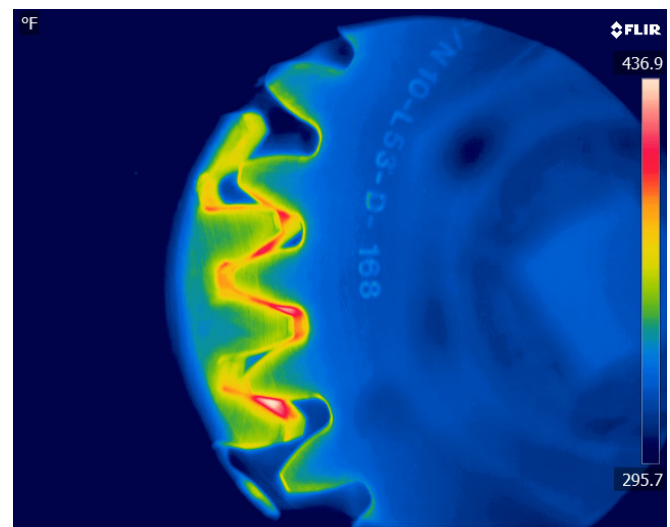


Figure 22. Thermal image of unshrouded gear a short time after initiation of loss-of-lubrication (10000 rpm, 59.3 N*m (525 in*lb)).

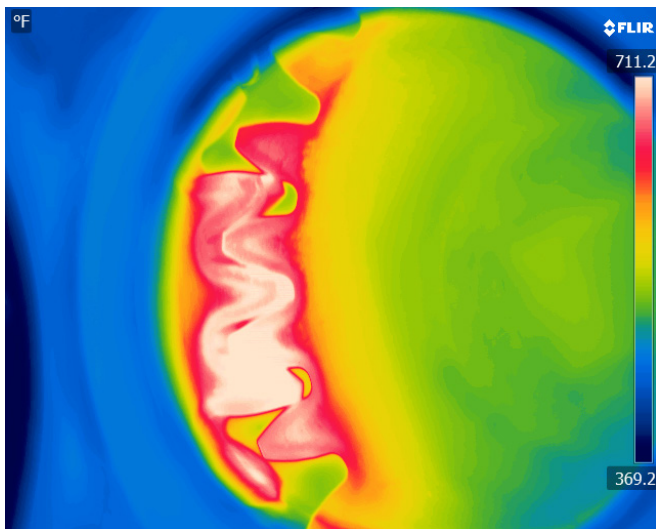


Figure 23. Thermal image of unshrouded gear nearer to test completion. (10000 rpm, 59.3 N*m (525 in*lb))

CONCLUSIONS

Loss-of-lubrication tests were conducted in an aerospace simulated environment using consistent sets of test hardware. The following is a summary of the test results:

1. Applied torque can have a drastic effect on loss-of-lubrication time. An increase of torque by 40%, 59.3 to 83.6 N*m (525 to 740 in.-lb) resulted in a decrease in average loss-of-lubrication operation time by 75% (42 to 8 min).
2. Operation in loss-of-lubrication mode at lower torque produced an elevated steady state temperature condition. The higher torque level did not have this operating time at an elevated steady state temperature condition. During the higher torque tests, the temperature continued to increase until failure of the teeth.
3. On-component thermocouple data for shrouded or unshrouded gears revealed that the gear under normal conditions have bulk temperatures that are 11 to 22 °C (20 to 40 °F) higher than the fling-off temperatures measured by the static shroud thermocouples.
4. On-component thermocouple data for shrouded or unshrouded gears indicated that during loss-of-lubrication, conditions bulk temperatures on the gear are from 80 to 275 °C (150 to 500 °F) higher at certain times during this test when compared to the static shroud temperatures.
5. A comparison between instrumented shrouded and unshrouded gears was made. Unshrouded gears operated at slightly lower temperature ~ 45 °C (80 °F) than shrouded during the “steady state” elevated portion of the loss-of-lubrication tests.
6. A high-speed, full-field, infrared thermal imaging system was utilized in the unshrouded and instrumented gear test. The results attained agreed with that found using thermocouples. Full field thermal data provides information that will be necessary for validating future modeling efforts.

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